Overcoming Rail-End Bolt Hole Cracking by Cold Expansion Pre-Stressing

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Abstract

Cracking at rail-end bolt holes is a major safety concern being the attributable cause of a number of derailments. It is also a cause of premature rail replacement, imposition of rail speed restrictions and a significant factor in rail inspection and maintenance costs. The problem can be overcome by pre-stressing the bolt hole to induce residual compressive stresses around these holes. This paper reviews a hole treatment process called split sleeve cold expansion, developed by Fatigue Technology Inc. (FTI) for the aerospace industry to virtually eliminate fatigue cracks originating in holes. The paper describes how this technology is being used to significantly reduce the incidence of rail-end bolt hole cracking.

Exhaustive testing and field evaluation by the U.S. Department of Transportation (DOT) and British Rail Research confirmed the effectiveness of this method in minimizing or preventing fatigue cracking. The result is safer operations and long-term cost benefits to rail operators through extended inspection intervals and possible allowance of higher axle loads. Split sleeve cold expansion is an economical and reliable method to pre-stress bolt holes during routine track maintenance or manufacture of new rail, joints and switches. The technology can also be applied to other rail structures and components such as wheels and bridges.

Rail-End Bolt Hole Cracking Problem

Bolt-hole cracking is not unique to any specific railway, region or country, but it is recognized as a worldwide problem. In the United Kingdom during the early 1980s, more than 3000 cracked and broken rails of different types were reported each year. The highest number of defects was reported on middle-speed-range, heavily loaded track. Of these, about 25% were caused by cracks originating at rail-end bolt holes, or about 750 per year. Between 60 and 70% of rail-end cracks were detected before they had grown completely through the track. From these statistics one can calculate that over 200 rail-end bolt holes completely failed before detection or repair.

In 1974, the U.S. National Transportation Safety Board identified broken rails as the largest single cause of train accidents [1]. Between 1982 and 1988, track-related accidents represented between 30 and 40% of the total number of reported accidents [2]. U.S. Federal Railroad Administration statistics for 1988 [3] showed that derailments caused by bolt hole failures accounted for 10% of the total cost of rail and joint bar defects.

More recently, tests were carried out as part of the Heavy Axle Load (HAL) program for the U.S. rail industry [4] to investigate the effect of increased axle loads and speeds on existing track. It was found that an increase in axle load of only 20% precipitated serious cracking in bolt holes at turnout frogs and switches.

The economic impact on a country or region that relies on a rail network to transport raw material, goods or people can be severely impacted by rail closure due to derailment or unscheduled repair/rail replacement. When such derailments involve dangerous chemicals or flammable materials in populated areas, the consequences can be catastrophic. Accidents involving death or injuries to passengers are unacceptable in most societies and therefore it is imperative to minimize the potential of any accident-causing mechanism.

Joint Failure Mechanism

Cracks originating from rail-end bolt holes are the result of the repetitive loads applied from each wheel as it passes over the joint as shown in Figure 1. The shear stress in the rail caused by the bending moment from the force of the wheel and the impact of the advancing wheel on the joint, is concentrated at the bolt hole. Additionally, the shear stress associated with dynamic wheel/rail forces generated by a dynamic dip at the joint, combined with high cyclic stresses, eventually cause cracks to initiate and grow in the lead bolt hole. These cracks propagate along a 45-degree plane as a classic fatigue failure. If cracks are not detected before they become critical, usually 5 to 10 mm long, fracture can occur. Loose or poorly supported joints can further increase the magnitude of the stress at the hole and any scratches or corrosion pits that may be present in the hole can further exacerbate crack initiation. Undetected rail-end bolt hole cracking can lead to the separation of a significant end piece of the rail (as shown in Figure 2), potentially causing derailment.

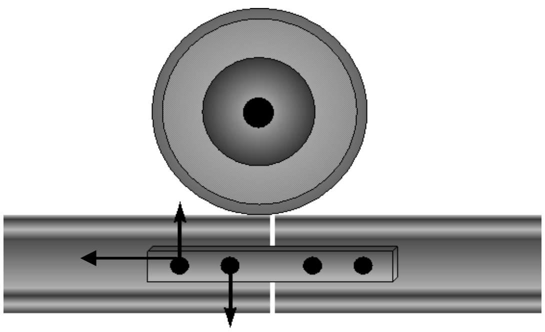

Figure 1. Fatigue Loading of Typical Rail Joint

Figure 2. Example of Separated Piece of Track End

Fatigue Life Improvement of Rail Joints

A number of significant attempts have been made over the past 30 years to overcome the problem of rail and bolt-hole cracking from increasing the web thickness of the rail to proportionally reduce the high stresses, to "work-hardening" the hole surface to increase the fatigue resistance locally. The processes used were difficult to control and none of these methods proved to be effective.

The U.S. Department of Transportation (DOT) sponsored a study in 1975 [5] to investigate the application of several promising fatigue life enhancement techniques to rail bolt holes. These methods included pad coining, interference fit bolts and split sleeve cold expansion. The lives of specimens treated with split-sleeve cold expansion showed a remarkable life improvement over non-cold expanded bolt holes and the other methods investigated. Figure 3, from the DOT study, shows the dramatic improvement in rail life after the application of cold expansion. Independent British Rail trials and evaluation of the cold expansion process, including laboratory and in-service tests [6], confirmed the results and concluded that the process increased the life of a bolted rail joint by a factor of 10 or more by reducing or eliminating bolt hole fatigue failure.

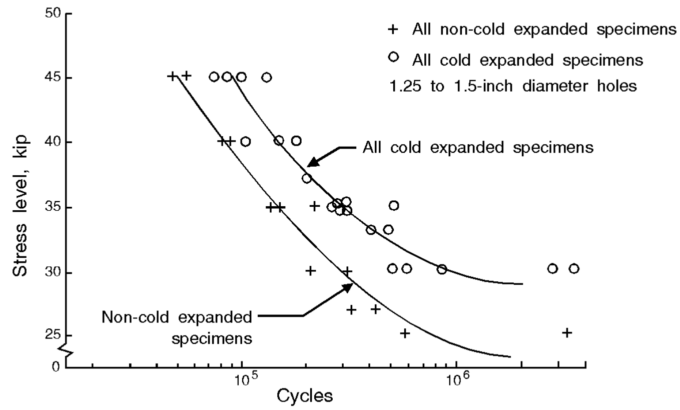

Figure 3. Increase in Fatigue Life for Cold Expanded Holes (U.S. DOT Rail Fatigue Results)

The Split Sleeve Cold Expansion Process

The split sleeve cold expansion process is accomplished by pulling an oversize tapered mandrel, pre-fitted with a dry-film lubricated split sleeve through the bolt hole using a specially designed hydraulic puller, as shown in Figure 4. The sleeve remains in place in the hole during the expansion process and is afterward discarded. The sleeve protects the hole from sliding metal contact of the mandrel and ensures the hole is radially expanded. The dry-film lubricant in the sleeve minimizes the pull force required to pull the mandrel through the hole.

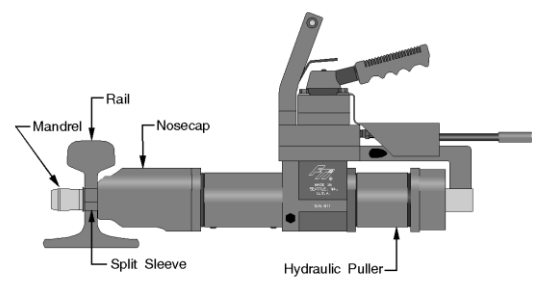

Figure 4. Schematic of Split Sleeve Cold Expansion Process

The combination of the mandrel diameter and the sleeve thickness creates enough radial expansion to significantly yield the material around the hole. The applied expansion for the process in rail applications range from 2 to 4% of the hole diameter, depending on the material properties of the steel and the hole diameter. After the mandrel passes through the hole, the area around the hole remains residually stressed in compression. The peak magnitude of the residual compressive stress is roughly equal to the compressive yield strength of the steel and extends about one diameter from the hole edge. A balancing zone of tensile stress, about 10 to 20% of the tensile yield stress, surrounds and “locks in” the beneficial compressive stress, as shown schematically in Figure 5. The residual compressive stresses lower both the mean and maximum cyclic stress at the edge of the hole. This reduced net stress retards crack initiation and inhibits crack growth.

An important consideration is that cold expansion of the hole alone may not prevent crack initiation, although it will significantly retard it. Defects resulting from hole drilling/reaming or corrosion pits and metallurgical inclusions could also initiate a crack. The residual compressive stress retards crack growth by reducing the stress intensity factor range (ΔK) (shown in Figure 6). This reduction in stress intensity was also reported in British Rail studies of the process [7]. Additionally, the presence of residual stresses may change the critical crack length for unstable fracture. The lower crack growth rates and greater critical crack length can be used to extend non-destructive inspection intervals of rail joints, thereby reducing operation and maintenance costs of rail networks.

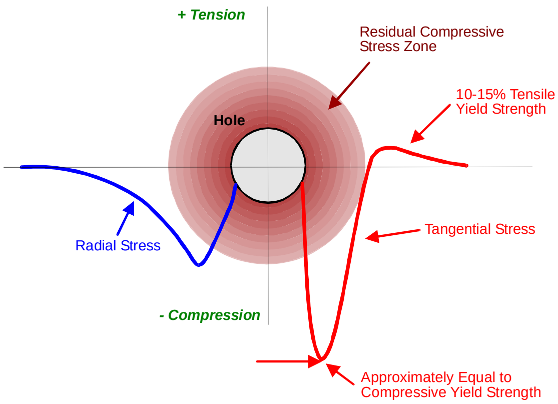

Figure 5. Distribution of Residual Stress Around a Split Sleeve Cold Expanded Hole

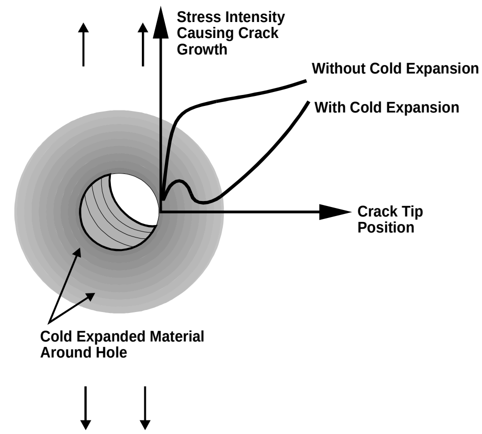

Figure 6. Reduction in Stress Intensity Factor Range (ΔK) in a Cold Expanded Hole

FTI RailTec Process

To facilitate cold expansion of rail-end bolt holes Fatigue Technology developed the RailTec™ cold expansion system of tooling to incorporate the process in existing track as well as new production rail. This rugged system of tooling was designed for a range of standard rail bolt holes and for the demands of the track environment. In a typical field application, as used by rail crews, each joint is dismantled, followed by cleaning of bolt holes and adjacent areas. Holes are measured and cleaned up with a bridge reamer to a nominal size and then each hole is cold expanded using RailTec tooling, as shown in Figure 7. Finally, the joint is re-assembled. Trained operators can process around 40 holes per hour.

Figure 7. RailTec System in Use on Existing Track

For new rail production the bolt holes are reamed to the appropriate diameter and cold worked using equipment similar to the field repair equipment.

The estimated total cost of servicing the joints during maintenance, including cold expansion of all holes, is about $3000 per Km. This compares to the cost of converting jointed track to Continuous Welded Rail (CWR) at around $180,000 per Km [8]. The cost of CWR can be prohibitively high for relatively low-revenue earning lines or third world countries, and requires the track to be out of service for a much longer period of time.

In-Service Results

In-service evaluations of cold working show the dramatic effects of the process on rail-end bolt hole cracking. In the UK, the Exeter to Sherbourne route comprises 38 km of track. Prior to a cold working maintenance action that started in 1987, the line was plagued with rail-end bolt hole cracks in the form of star cracks. By 1991 the entire route was treated and the number of incidences of star cracking reduced from 25 in 1987 to just 1 in 1991 as shown in Figure 8. A similar result came from a study of the Plymouth to Penzance route shown in Figure 9. Again, the high incidence of star cracking was reduced by cold expanding holes. These results [9] justified the widespread use of cold expansion in the UK.

Following its participation in the U.S. evaluation program, Union Pacific Railroad implemented the split sleeve cold expansion process on all new rail, switches and crossings.

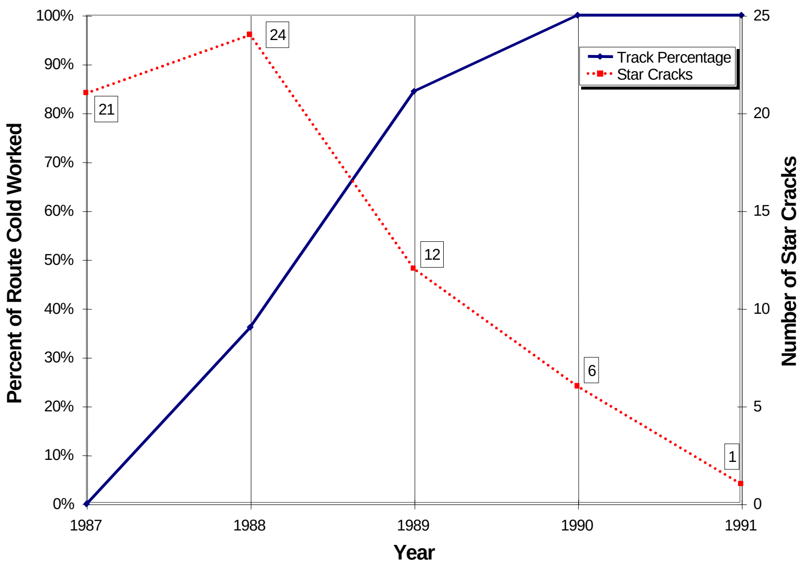

Figure 8. Survey of Results After Cold Expansion - Plymouth to Penzance Route

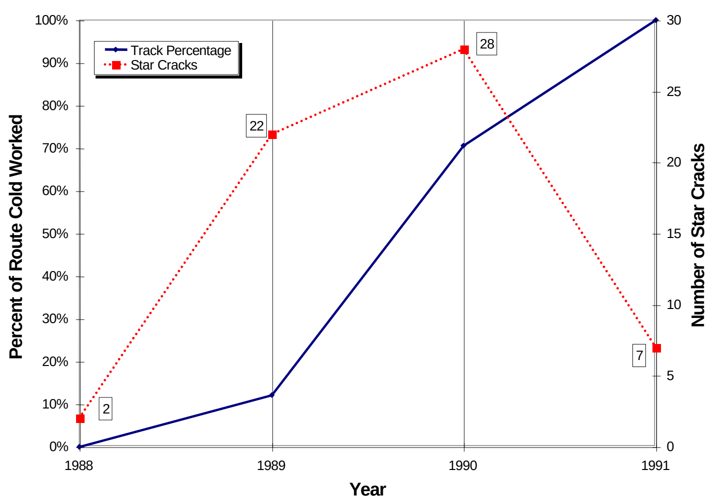

Figure 9. Survey of Results After Cold Expansion - Exeter to Sherbourne Route

In this Asian region, the Mass Transit Railway Corporation (MTRC) of Hong Kong has been using the cold expansion process for a number of years. The process was introduced to overcome bolt hole cracks in standard carbon BS90A rails used in the original rail system. MTRC reported that following implementation, the rate of crack development dropped significantly. What they found was that hole cold expansion moved the fatigue cracking problem away from the holes to the underside of the rail head. This other problem is exacerbated by the difficulty in achieving good joint alignment with concreted track. Nevertheless, failure rates as a whole have dropped significantly justifying the time and money spent on the cold expansion process.

Summary

The problem of rail-end bolt hole cracking can be virtually eliminated by the use of split sleeve cold expansion as verified by laboratory studies, carefully controlled field surveys and in-service results. The residual compressive stress induced by the RailTec process, effectively reduce the local stress levels and inhibit crack growth. The process is used in routine maintenance in the United Kingdom and the United States and is applied to existing track; new or replacement bolted track, switches, crossings and insulated joints. RailTec is also used in the Hong Kong MTRC where the rate of crack development dropped significantly. Hole cold expansion has also been successfully used to prevent cracks emanating from balance weight holes in rail wheels. Studies show that increased axle loads and speeds increase the probability of rail-end bolt hole cracking. Cold expansion of these joints reduces the probability of cracking by allowing the joint to operate at higher stress levels. Inducing residual compressive stresses around rail-end bolt holes improves safety of operations by eliminating a potential cause of derailment. It also leads to more economical rail operations by extending inspection intervals and reducing routine and special maintenance costs.

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